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(54) Feedback control of mechanical breathing aid gas flow

(57) A feedback controller (1) for regulating respiratory gas in a mechanical breathing aid system (2,3,4) comprises comparator means (9) for periodically generating in a current breathing cycle an error signal (10) representing the difference between a value (7) of a gas parameter measured for gas within the system and a target value (8) of the gas parameter; and a control signal generator (11) for processing the error signal (10) in accordance with a control function to generate a control signal (12) usable in the regulation of the respiratory gas and having a variable value integral gain means (20) providing an input to an integrator element 21. Adaption means (19) is arranged to determine for the current breathing cycle an extreme value of the periodically generated error signal (10) and to vary the value of the integral gain used in the gain means (20) for a next breathing cycle dependent on a rate of change of the value of the extreme error signal with value of the integral gain.

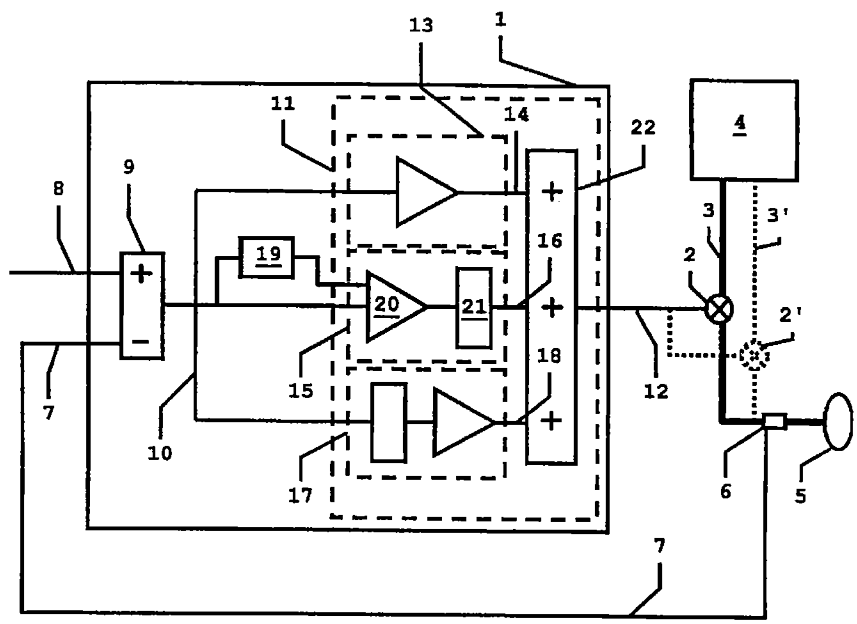

FIG. 1

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Description

[0001] The present invention relates to an apparatus and method for the feedback control of respiratory gas flow within a mechanical breathing aid and in particular to an apparatus and method for the adaptive feedback control of the gas flow.

[0002] Feedback controllers are used within a mechanical breathing aid, such as a ventilator system, to adjust gas flow rates based on a measurement of a system gas parameter, for example gas pressure, rise time, or flow rate, in order to achieve and maintain the value of that variable at or within an operating range of a target value. These controllers are usually operably connected to a flow control regulator, such as a solenoid valve, to provide a control signal used to adjust the opening of the valve. How the adjustment is made to reach the target value depends not only on the measured value of the system flow parameter that is fed back to the controller but also on additional parameters known as control parameters. These control parameters directly affect the performance and stability of the controller and their optimal values may change with time as system properties, such as compliance and resistance, vary. A mechanical breathing aid is particularly problematical to control in this manner since its pneumatic system includes (or is connected in use to) a patient's respiratory system, including lungs the compliance and resistance of which can change unpredictably with time and with patient.

[0003] In order to overcome this problem it is known to provide controllers having control parameters which automatically vary or "adapt" with changes in properties of the ventilator system. One such controller which provides an adaptation for a next breath that is based on the analysis of gas delivery in previous breaths is disclosed in US 5,271,389. This controller comprises comparator means for periodically generating in a current breathing cycle an error signal representing the difference between a value of a gas parameter measured for gas within the system and a target value of the gas parameter, a control signal generator for processing the error signal in accordance with a control function having a variable value control parameter to generate a control signal usable in the regulation of the respiratory gas, and adaption means for varying the value of the variable value control parameter responsive to the error signal. The adaption means operates by summing the error signal in a particular period with all past error signals for the corresponding period of past breaths to provide a cumulative error signal which is used to vary the control parameter for the same period of the next breath. Thus the correction will "improve" as the error values from more breaths are added to the cumulative signal.

[0004] It is an aim of the present invention to provide an adaptive feedback control of gas flow within a mechanical breathing aid system in which the adaption may be made on a breath-by-breath basis without the need to rely on a cumulative error signal.

[0005] This is achieved by the controller according to and characterised by the present claim 1. By providing for the adaptive variation of a variable control parameter for a subsequent breathing cycle which is based on the change of an extreme error signal value (that is a maximum or a minimum value depending on how the error signal is derived and which phase of the breathing cycle is being controlled) with value of control parameter, then disturbances in a breathing aid system may be automatically compensated for based on the past performance of the system and typically based on the performance of the system over consecutive breathing cycles without the need to establish a cumulative error signal.

[0006] Preferably an integral gain control parameter is varied assuming a linear relationship between an extreme pressure error signal and the value of the integral gain parameter. In a feedback controller, such as a PID or PI controller in which respectively a 'proportional-integral-derivative' and a 'proportional-integral' control function is implemented it is the integral gain parameter that is found to be highly sensitive to disturbances in the pneumatic system such as changes in lung resistance and compliance.

[0007] The invention will now be described, by way of example only, with reference to the drawings of the accompanying Figures, of which:

Fig. 1 is a schematic diagram of a section of a ventilator system including a feedback controller according to the present invention.

Fig. 2 shows a flow chart of the operation of an adaption means of the feedback controller of Fig. 1.

Fig. 3 shows a flow chart for the calculation of the rate of change of I gain by the adaption means the operation of which is shown in Fig 2.

Fig. 4 shows a flow chart for the calculation of I gain from the rate of change calculated according to the steps of Fig. 3.

[0008] Considering now Fig.1, a feedback controller 1 is shown which is adapted to control one or both an inspiration gas flow control valve 2 and an expiration gas flow control valve 2'. These valves 2,2' are respectively disposed in an inspiration gas flow path 3 and an expiration gas flow path 3' of a respiration gas which passes between a ventilator unit 4 and a patient's respiratory system 5. A sensor unit 6 is also provided within the flow path 3 (and also the flow path 3') to measure a gas pressure and has its output provided periodically (typically at a sample frequency of several kHz) as an input 7 to the controller 1. Also provided as an input to the controller 1 is a signal 8 representative of a desired or target gas pressure.

[0009] The feedback controller 1 comprises a comparator 9 which receives the input target 8 and actual 7 flow parameter signals for a particular breathing cycle and periodically generates an error value signal 10 representative of their difference; and a control signal generator 11 which receives the error value signal and uses it to establish a control signal 12 for periodically controlling one or both of the valves 2,2' during the breathing cycle.

[0010] The control signal generator 11 includes a proportional gain means 13 which receives the error value signal 10 and amplifies it by a predetermined amount to produce a proportional signal 14 component of the control signal 12; a an integration means 15 for producing an integral signal 16 component of the control signal 12; and a differentiating means 17 for producing a differential signal 18 component of the control signal 12. The feedback controller 1 of the present embodiment is thus of a type commonly referred to as a PID controller.

[0011] The feedback controller 1 also includes an adaption means 19 which receives the error signal 10 and determines first a maximum value of the error signals 10 that have been generated periodically during a predetermined portion of the breathing cycle and then, dependent on the so determined maximum value, a gain parameter for use in the next breathing cycle. This gain parameter is based on a calculation within the adaption means 19 of the rate of change of maximum value with value of gain parameter from previous breathing cycles stored within a memory (not shown) of the adaption means 19, as will be discussed in greater detail below.

[0012] The integration means 15 comprises an integral gain means 20 which receives the periodic error signal 10 and amplifies it by an amount dependent on the value of the gain parameter passed from the adaption means 19 before passing it to an integrator element 21 where it is integrated to provide an integral signal component 16 of the control signal 12. A summing element 22 sums the proportional signal component 14, the integral signal component 16 and the differential signal component 18 and outputs the sum for use as the control signal 12.

[0013] Assuming, for the present embodiment, that the controller 1 is adapted to control the inspiration valve 2 during an inspiration phase of a breathing cycle. In controlling the flow valve 2 it is desirable to provide a small initial overshoot (O) of the target pressure since with an overshoot (O) a smaller rise time will result. However the overshoot (O) should not be too great since this may cause discomfort and even injury to a patient's respiratory system 5. The overshoot (O) is therefore intended to be controlled to lie within upper (a) and lower (b) limits. The maximum value of the error signal 10 then is a measure of this overshoot (O) and may be a negative value, which in this case would represent an undershoot. By arranging for the integral gain (I), used in the integral gain means 20, to adapt its value depending on the size of this overshoot (O) a feedback controller 1 can be provided that is responsive to the type of lung 5 connected to the flow path 3 as well as to changes within the flow path 3 itself. This is because the size of the integral gain (I) is highly dependent on the mechanical resistance and compliance of the pneumatic system 3,5.

[0014] Now, assuming a linear relationship between the overshoot (O) and the integral gain value (I) which is used in the integration means 15, the desired integral gain value (I3) required to provide a satisfactory overshoot (O3) in a next breath is given by

$$I3 = I2 + [(I1-I2)X(O3-O2)/(O1-O2)] \qquad (1)$$

where

I1 and O1 are respectively the gain value and the overshoot associated with a previous breath (preferably the immediately preceding breath);

I2 and O2 are respectively the gain value and the overshoot associated with the current breath;

[0015] If the value of the desired overshoot (O3) for the next breath is selected to lie midway between the limits a,b of an acceptable overshoot then equation (1) may be re-written as

$$I3 = I2 + [(I1-I2)X(((a+b)/2)-O2)/(O1-O2)] \qquad (2)$$

[0016] With (O1-O2)/(I1-I2) written as dO/dI, the rate of change of overshoot with gain value, then equation (2) can be expressed as

$$I3 = I2 + [((a+b)/2)/(dO/dI)] \qquad (3)$$

[0017] Considering now Fig. 2, Fig. 3 and Fig. 4, flow charts for the operation of the adaption means 19 are shown. The first step 23 is to calculate within a specified time period from the beginning of an inspiration phase (which is typically of the order of 100ms for adults and 200ms for neonates) a maximum error signal, Emax, from periodically determined error signals 10 input during this period as an error value E. This first step 23 includes a step 24 of comparing the presently input error value E with a stored value of Emax obtained during the specified period of the current breathing cycle and either replacing (step 25) the current value of Emax with the value E of the current error signal 10 or maintaining (step 26) the stored value of Emax. After the specified period a step 27 is performed making the last stored value of Emax the value of the overshoot (O2) for the current breath. A step 28 is made to decide whether or not a new value of the integral gain should be provided as the integral gain control parameter (I3) for the next breath. If the overshoot (O2) for the present breath falls outside the predetermined limits a,b then a

new value of integral gain control parameter (I3) is determined (step 29) for use in the next breath.

[0018] The step 29 of determining the gain control parameter (I3) comprises a step 30 (Fig. 3) of calculating a rate of change of overshoot with integral gain control value (dO/dI) and based on this value a step 31 (Fig. 4) of calculating the gain control parameter (I3) for use in the integral gain means 20 of the feedback controller 1. The step 29 of gain control calculation may need to be carried out iteratively until the overshoot (O) lies within the desired upper (a) and lower (b) limits since the linear relationship is only an approximation which is better for consecutive breaths.

[0019] In calculating the value dO/dI (step 30 of Fig. 3) it is first determined (step 32) whether the overshoot O2, associated with the current breath, is equal to that overshoot O1, associated with a previous, preferably immediately preceding, breath. If it is, or if it is not but it is determined (step 33) that the current gain control value I2 and the previous one I1 are the same, then dO/dI maintains its previous value (step 34) when the new gain value I3 is calculated (step 31). If the overshoots O2 and O1, and the integral gain control parameters I2 and I1, differ then the value (dO/dI) is calculated (step 35). If this value lies within limits (step 36) that are selected to discriminate against inaccuracies in measurements made then this value is used in the calculation of the new I gain (step 31) I3. If the value dO/dI lies outside these limits then dO/dI is set to MAX (step 37) and this value used in calculating the new integral gain (step 31) I3. The lower limit used at step 36 is here chosen as 0 since a change in I gain is expected to provide a change in overshoot and the upper limit as a maximum allowable value MAX above which an unexpectedly rapid change indicative of a spike or 'glitch' is considered to have occurred.

[0020] The step 31 (Fig. 4) of calculating the gain value I3 comprises a first step (step 38) of determining whether a patient is connected to the ventilator 4.

[0021] If a patient has been disconnected for some reason, for example for the removal of a secretion from a patient's throat, then the new gain value I3 is set to the current gain value I2 (step 39). This is done in order to prevent a 'run away' gain value I3 being set up which may lead to a patient being exposed to dangerous pressure levels when re-connected. Otherwise a new gain value I3 is calculated (step 40) using equation (3). If the difference between this new gain value I3 and the current gain value I2 lies within pre-set limits (Imin and Imax in step 41), selected to ensure that not too extreme a pressure can be delivered to the patient, then the value of I3 that was calculated at step 40 is provided for output (step 42) for use within the integral gain means 20 of the integration means 15. If this difference, calculated at step 41 is less than the lower limit, Imin, then I3 is set to I2-Imin (step 43). If this difference, calculated at step 39, is greater than the upper limit, Imax, then I3 is set to I2+Imax (step 44). The new value of the integral gain control parameter I3 is then output at step 42 for use within the feedback controller 1 in the regulation of the valve 2 in an inspiration phase of the next breathing cycle.

[0022] It will be appreciated that an expiration pressure within the gas flow path 3' may be controlled, for example to maintain a pre-determined PEEP level, in a manner similar to the one described above in respect of inspiration pressure regulation. In this case the expiration valve 2' is controlled by the feedback controller 1 modified to provide adaptive regulation of the expiration pressure. The adaption means 19 will operate principally according to the flow charts shown in Figs. 2 and 3 but using different limits and a different time period which an extreme value of error, E, will be determined. Typically this time period begins upon a detected condition that an error signal (defined as PEEP value - pressure measured at sensor 6) is greater than 0.5 cm H_2O and that the derivative of the error signal is negative. The time period ends a predetermined time, typically in the range of 100-200 ms, after it begins.

Claims

1. A feedback controller (1) for regulating respiratory gas in a mechanical breathing aid system comprising:

   comparator means (9) for periodically generating in a current breathing cycle an error signal (10) representing the difference between a value (7) of a gas parameter measured for gas within the system and a target value (8) of the gas parameter;
   a control signal generator (11) for processing the error signal (10) in accordance with a control function having a variable value control parameter (I) to generate a control signal (12) usable in the regulation of the respiratory gas; and
   adaption means (19) for varying the value of the variable value control parameter (I) responsive to the error signal (10); **characterised in that**
   the adaption means (19) is arranged to determine for the current breathing cycle an extreme value (Emax,Emin) of the periodically generated error signal (10) and to vary the value of the control parameter (I) for a next breathing cycle dependent on a rate of change of the value of the extreme error signal with value of control parameter.

2. A feedback controller as claimed in Claim 1 **characterised in that** the adaption means (19) is arranged to derive the rate of change for consecutive breathing cycles.

3. A feedback controller as claimed in Claim 1 or Claim 2 **characterised in that** the adaption means (19) is arranged to vary the parameter conditional on the value of the extreme error signal (Emax,Emin) lying outside a predetermined range of values (a,b).

4. A feedback controller as claimed in any of the Claims 1 to 3 **characterised in that** the comparator means (19) is adapted to generate the current error signal (10) representative of the difference between a measured gas pressure value (7) and a target gas pressure value (8).

5. A feedback controller as claimed in Claim 4 **characterised in that** the control signal generator (11) is adapted to execute a control function having the control parameter variable within limits selected to inhibit the presence within the system of a measured gas pressure value (7) less than the target gas pressure value (8).

6. A feedback controller as claimed in Claim 4 or Claim 5 **characterised in that** the control signal generator (11) comprises an integration means(15) having an integral gain means (20) operably connected to the adaption means(19) to receive a variable integral gain value (I) therefrom.

7. A feedback controller as claimed in Claim 6 **characterised in that** the adaption means (19) is arranged to vary the value of the integral gain value (I) in dependence of a linear relationship between the value of the extreme error signal (Emax,Emin) and the value of the integral gain value (I).

8. A method of regulating gas within a patient ventilator system comprising the steps of

   periodically determining a current error value in a current breathing cycle as the difference between a value of a parameter measured for gas within the system and a predetermined target value;
   periodically executing a control function dependent on the error value to regulate gas within the system, said control function having a variable value control parameter; and varying the control parameter dependent on the current error value and an error value generated in a previous breathing cycle;
   characterised in that
   the step of varying the control parameter comprises
   determining (23) in a current breathing cycle an extreme value of the periodically generated current error signal;
   determining (30) the rate of change of extreme value with control parameter; and
   calculating (31) the control parameter dependent thereon for use in the next breathing cycle.

9. A method as claimed in Claim 8 **characterised in that** executing a control function comprises executing an integral control function having an integral gain value as the variable control parameter.

10. A method as claimed in claim 9 **characterised in that** the step of periodically determining the current error value comprises measuring an actual gas pressure within the system and in that the step of calculating the control parameter comprises (40) calculating the control parameter dependent on a linear relationship between the extreme value of the current error signal and the value of the integral gain.

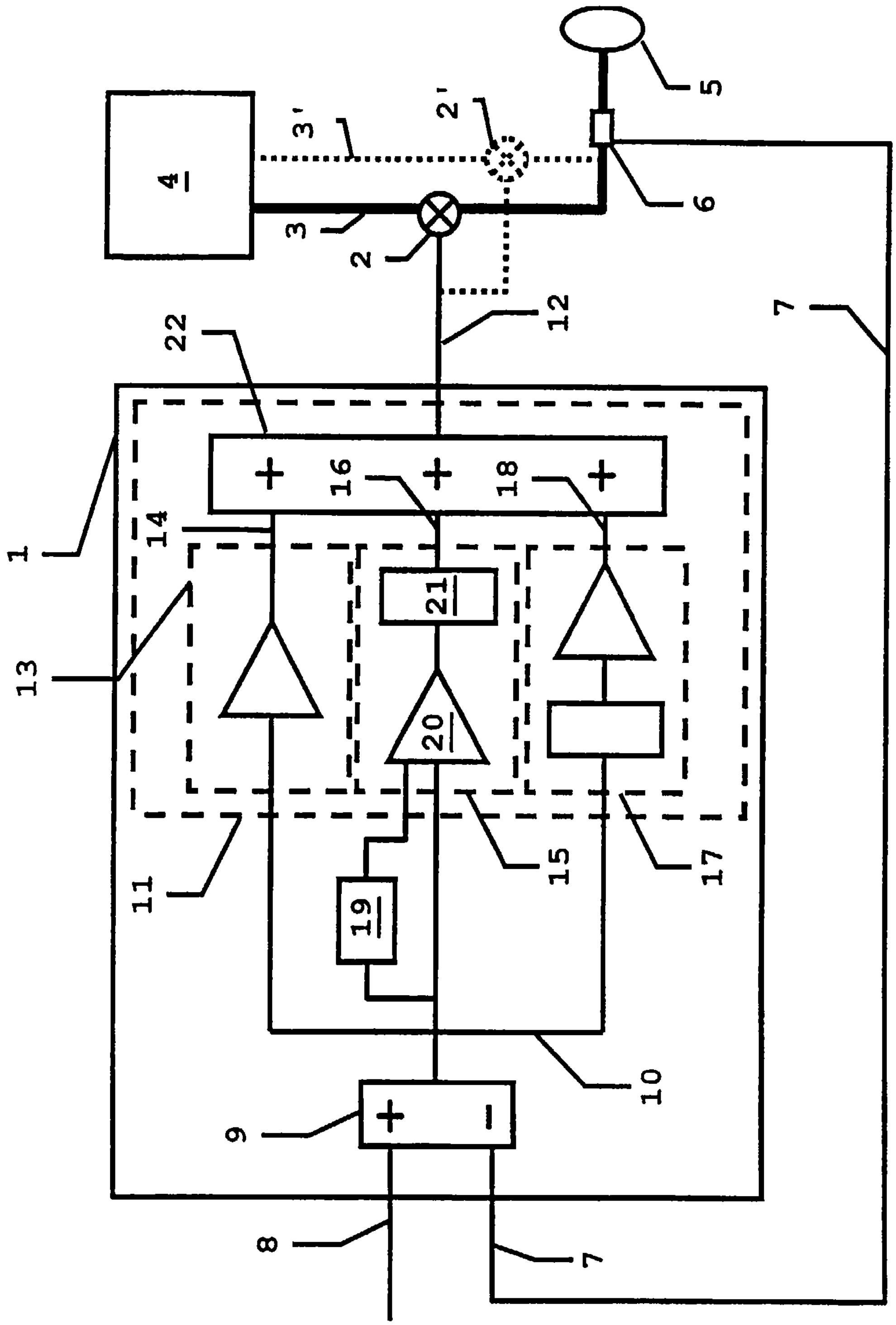


FIG. 1

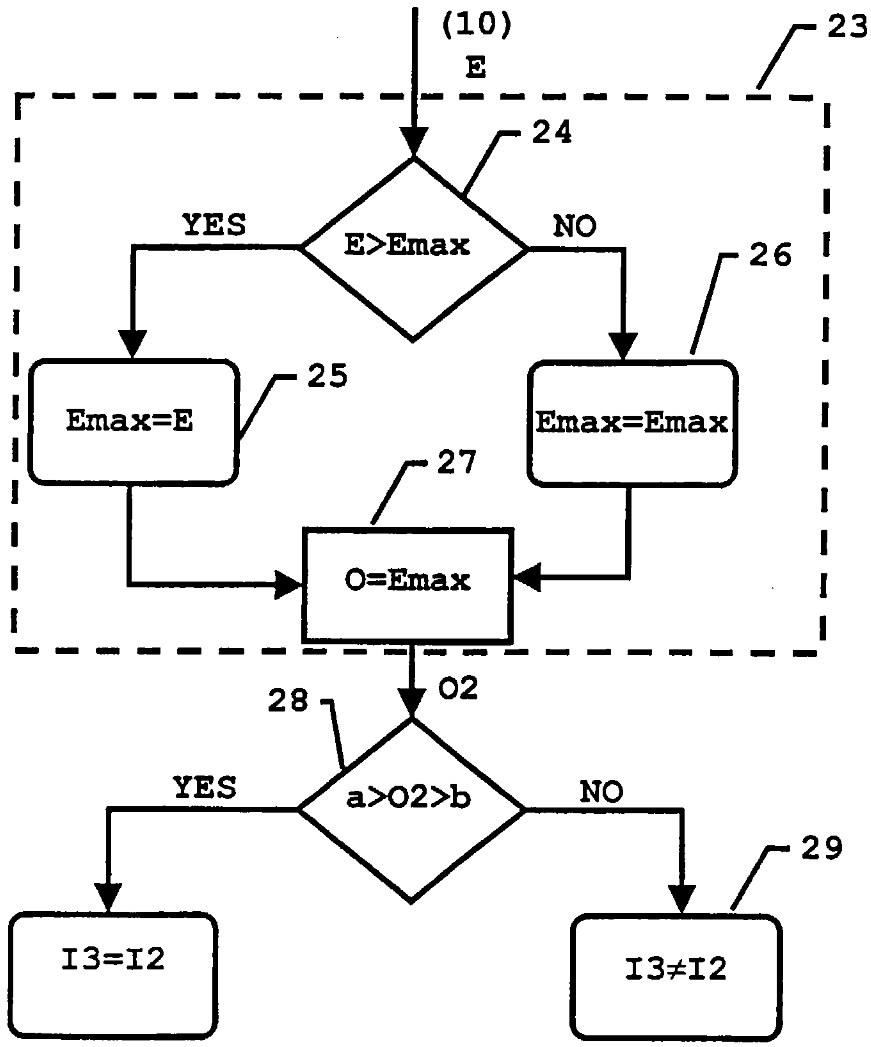
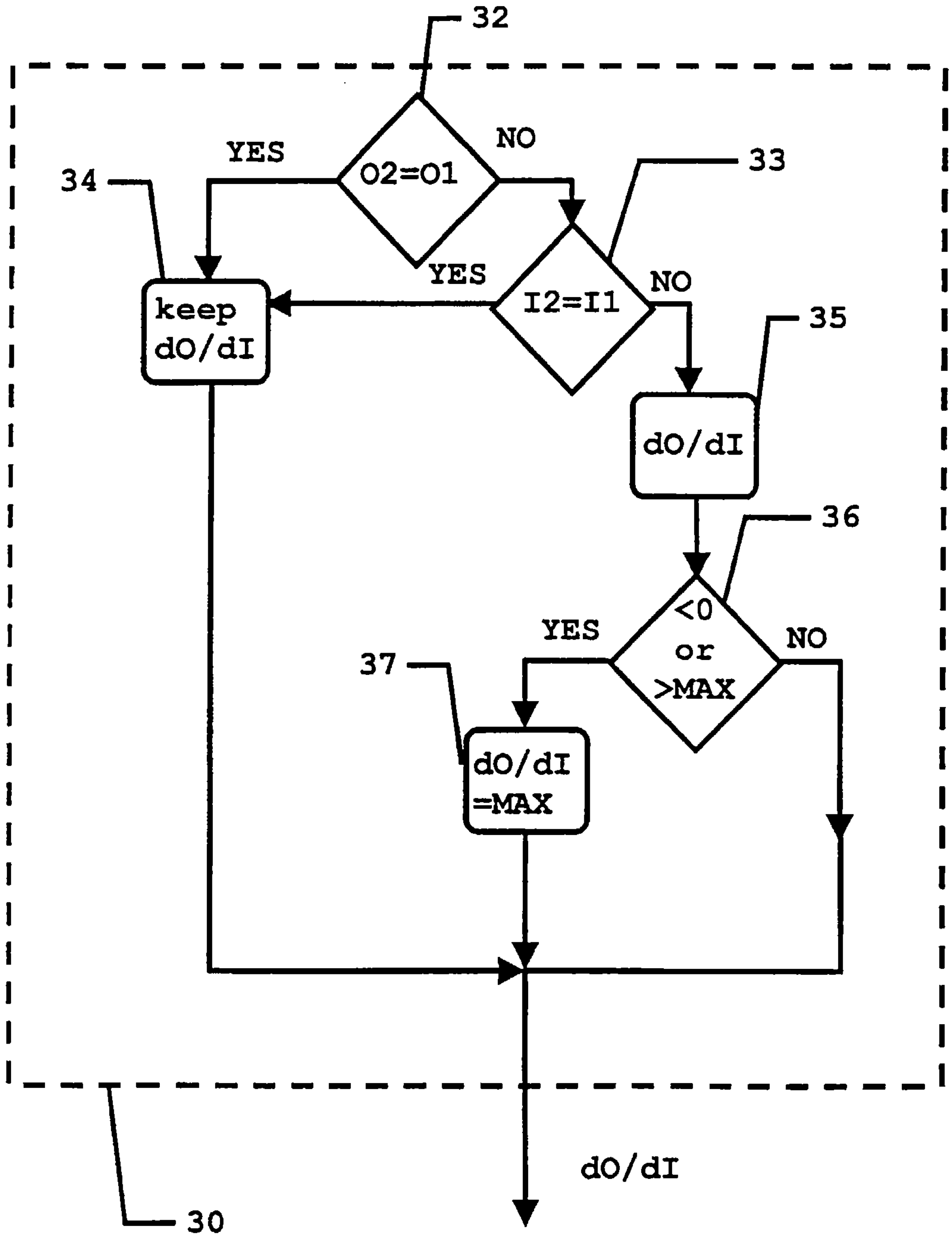

(10)
E
23
24
E>Emax
YES
NO
26
25
Emax=E
Emax=Emax
27
O=Emax
28
O2
a>O2>b
YES
NO
29
I3=I2
I3≠I2

FIG. 2


32
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YES
NO
33
34
keep
dO/dI
YES
I2=I1
NO
35
dO/dI
36
<0
or
>MAX
YES
NO
37
dO/dI
=MAX
dO/dI
30

FIG. 3

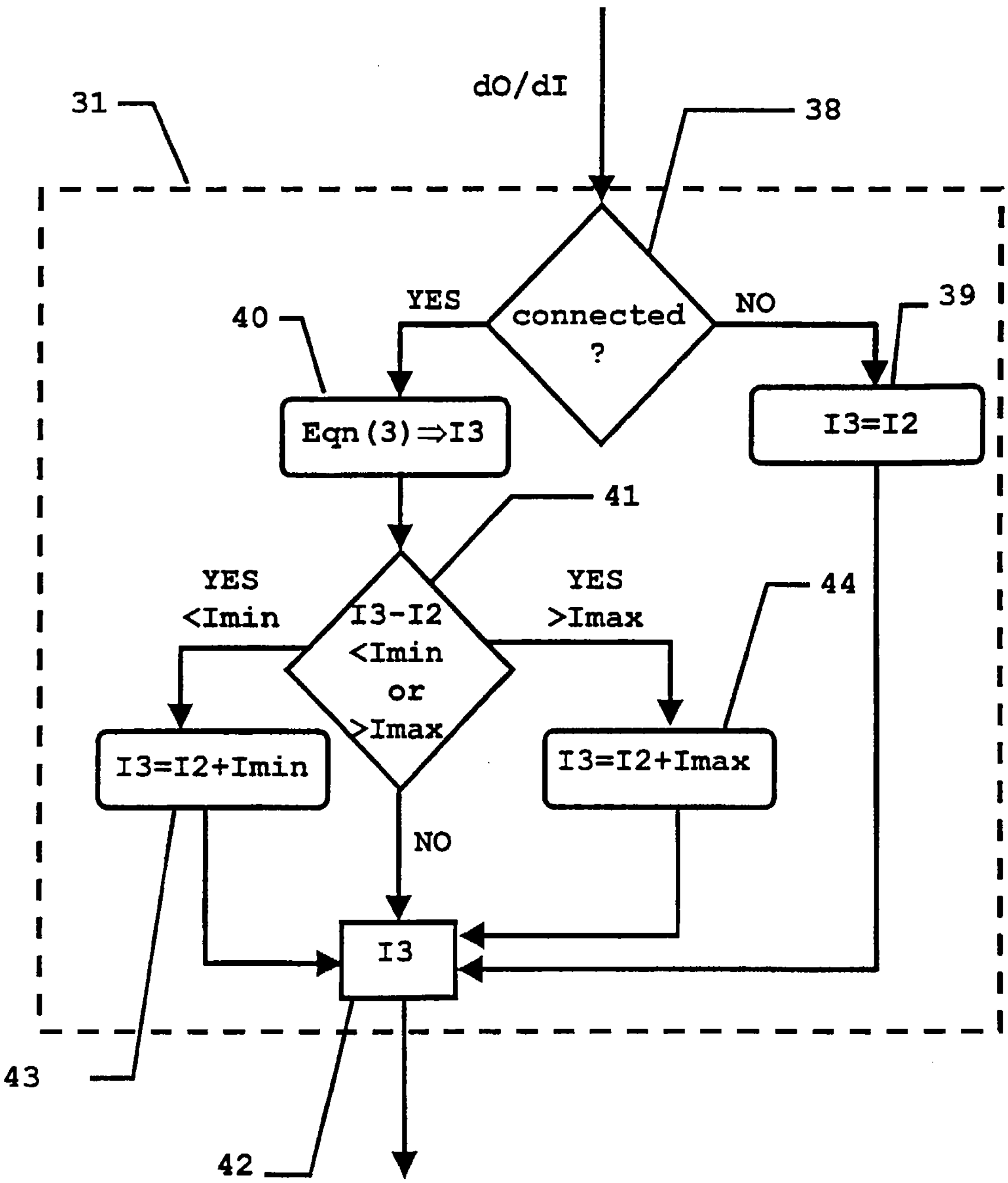
dO/dI
31
38
connected ?
YES
NO
40
39
Eqn(3)⇒I3
I3=I2
41
YES <Imin
YES >Imax
44
I3-I2 <Imin or >Imax
I3=I2+Imin
I3=I2+Imax
NO
I3
43
42

FIG. 4